New rules for single and built-up angle members

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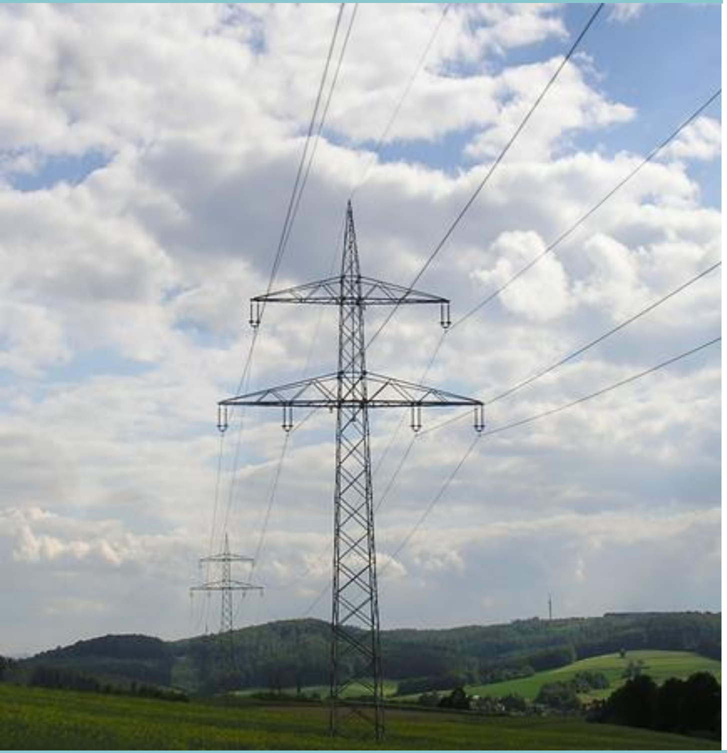

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supported by

European Commission

Research Fund for Coal & Steel

8 December 2020 – Innovative Developments and Solutions for Steel Lattice Towers

Objectives

- Development of design rules
  - Single angle members
    - Equal leg angles
  - Built-up members
    - Back-to-back connected members
    - Star battened members

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Single angle members
Introduction

- There are various codes and norms that may be used for the design of angles, as EN1993-1-1 and EN1993-3-1 with references to EN1993-1-5, EN50341.

- At the majority of the above-mentioned codes, the rules and formulae that are used have been developed mainly for I or H sections.

- There is also sometimes inconsistencies in between these normative documents and some rules are even missing.

- A "new" failure mode has been observed (segment instability), requiring also the development of a specific design formula

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There is a need of a full consistent set of formulae to cover the design of angles.

Single angle members
Objectives

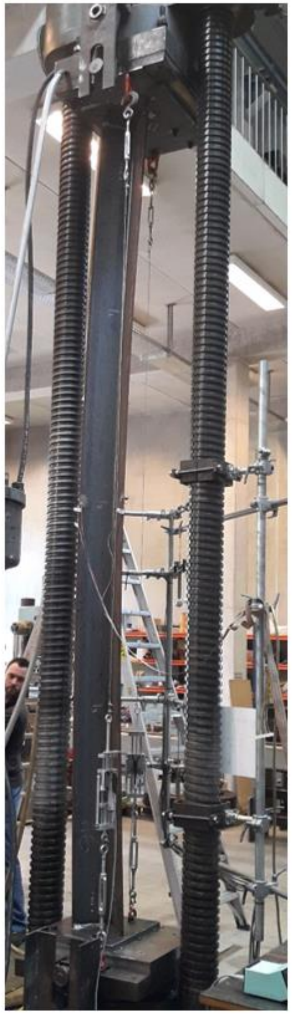
Objectives

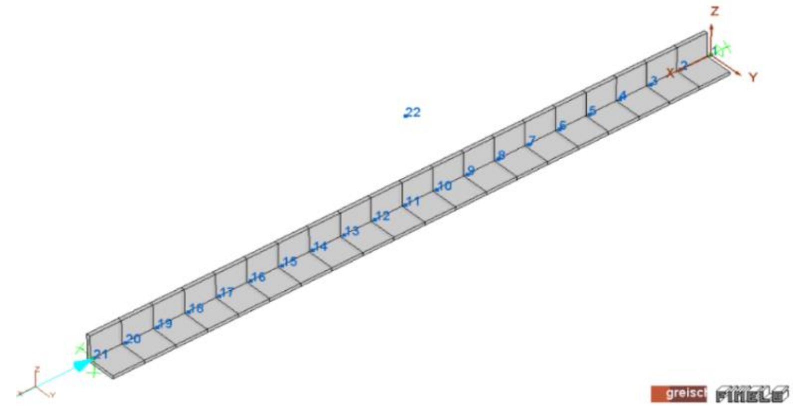
- Develop design rules for the classification and resistance of angle cross-sections, **under compression, strong and weak axis bending.**
- Develop design rules for the resistance and stability of member with an angle profile, **under compression, strong/weak axis bending, and combined compression and bending**

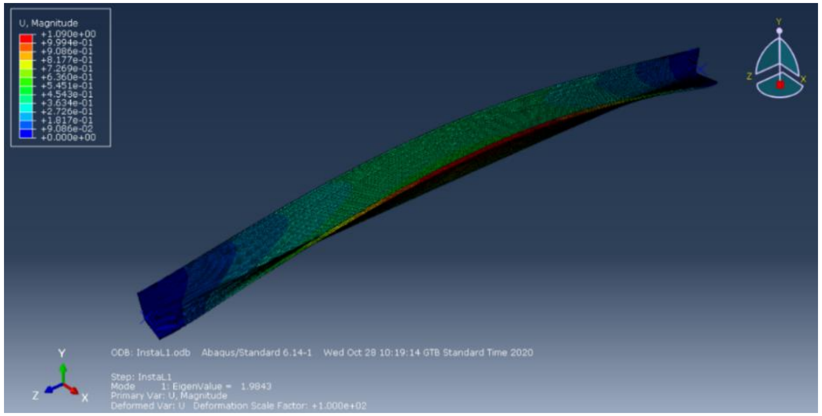
Methodology

- **12 laboratory tests** on large angle high strength steel columns
- Simulations to ensure the validity of the FEM model through the tests
- Parametrical **numerical studies** (approximately 400 simulations)
- **Analytical developments**

Single angle members
Objectives







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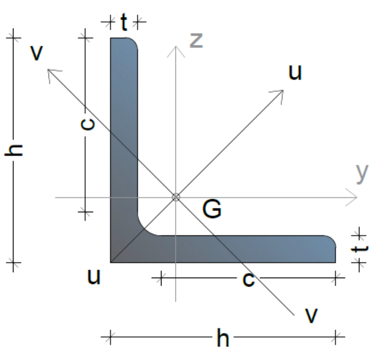
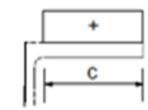
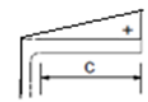
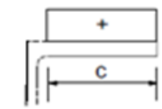
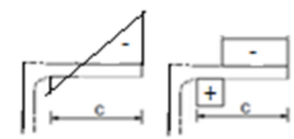
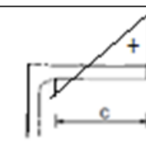
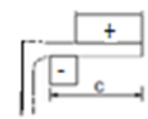
Single angle members
Classification system & Cross-section resistance

- The classification limit boundaries (even in pure compression) are based on the slenderness of the compression leg, and not, as often said, on the torsional instability mode.
- A pure torsional instability mode can be achieved **only** if the member is loaded at the shear center, what is not the case in pylons.



G	centre of gravity
h,t	geometrical properties (c=h-t-r)
u-u	major principal axis or weak axis
v-v	minor principal axis or strong axis
y,z	geometrical axes

	Comment	Class 3	Class 2
Compression N_c		 $\frac{c}{t} \leq 13{,}9\varepsilon$	
Strong axis bending M_u		 $\frac{c}{t} \leq 26{,}3\varepsilon$	 $\frac{c}{t} \leq 16\varepsilon$
Weak axis bending M_v	**Tip in tension**	 $\frac{c}{t} \leq 30\varepsilon$	
Weak axis bending M_v	**Tip in compression**	 $\frac{c}{t} \leq 26{,}9\varepsilon$	 $\frac{c}{t} \leq 14\varepsilon$

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Single angle members
Classification system & Cross-section resistance

<u>Class 3 limit</u>

1. limit prEN1993-1-1, Table 7.3, sheet 3:

(a) $\frac{h}{t} \leq 15\varepsilon \quad or \quad \frac{c}{t} \leq 18{,}75\varepsilon$

(b) $\frac{h}{t} \leq 11{,}5\varepsilon \; or \quad \frac{c}{t} \leq 14{,}37\varepsilon$

2. limit prEN1993-1-1, Table 7.3, sheet 2:

(c) $\frac{c}{t} \leq 14\varepsilon$

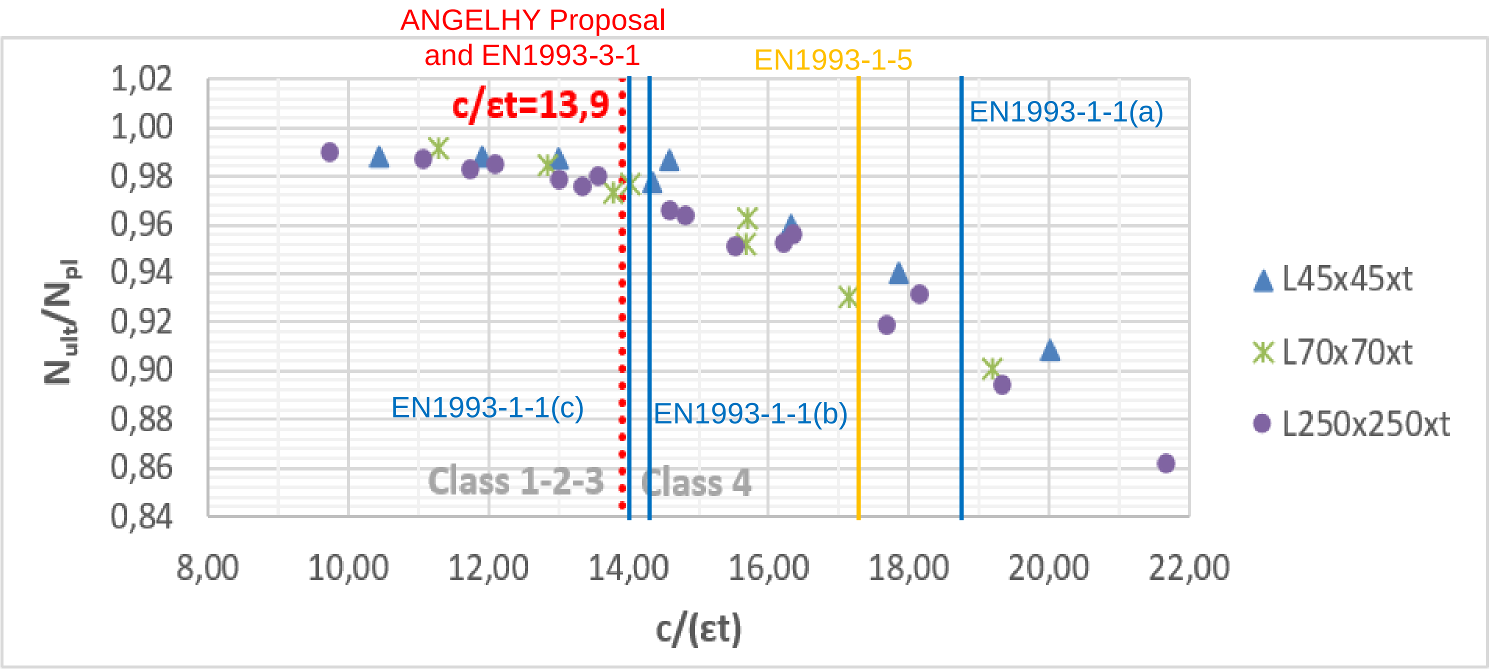
3. EN1993-1-5:

$\frac{h}{t} \leq 13{,}9\varepsilon \; or \quad \frac{c}{t} \leq 17{,}38\varepsilon$

4. EN1993-3-1:

$\frac{h}{t} \leq 15{,}9\varepsilon \quad or \quad \frac{h-2t}{t} \approx \frac{c}{t} \leq 13{,}9\varepsilon$

Inconsistency between the normative documents!



(c=0,8h)

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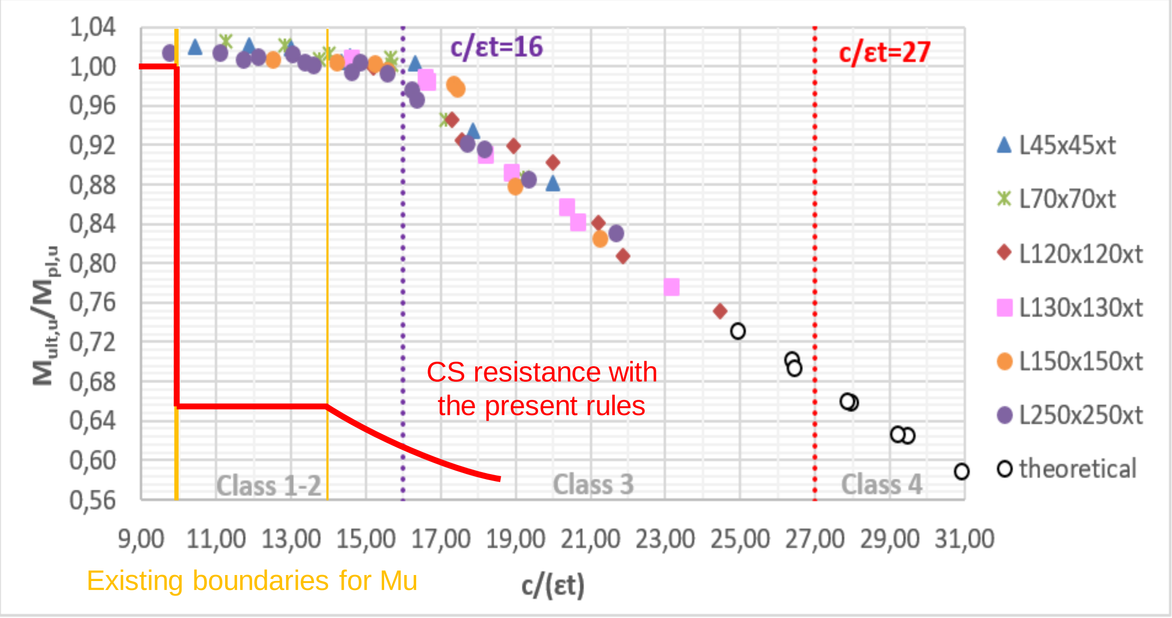
Single angle members
Classification system & Cross-section resistance

- Design formulae for angle cross-sections resistance in:
  - Compression
  - Strong axis bending M_u
  - Weak axis bending M_v

SEMI COMP results have been adopted→ linear transition between plastic and elastic cross-section resistance



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Single angle members
Member under pure compression – Flexural buckling

Design resistance - class 1,2,3: $N_{b,Rd} = \frac{\chi_{min} A f_y}{\gamma_{M1}}$

Design resistance - class 4: $N_{Rd} = \frac{\chi_{min} A_{eff} f_y}{\gamma_{M1}}$

where: $\chi_{min} = \min\{\chi_u, \chi_v\}$

$$\bar{\lambda}_u = \sqrt{\frac{A f_y}{N_{cr,u}}} \quad , \quad \bar{\lambda}_v = \sqrt{\frac{A f_y}{N_{cr,v}}}$$

χ_u, χ_v derived from buckling curves **a** and **b** (prEN1993-1-1:2019)

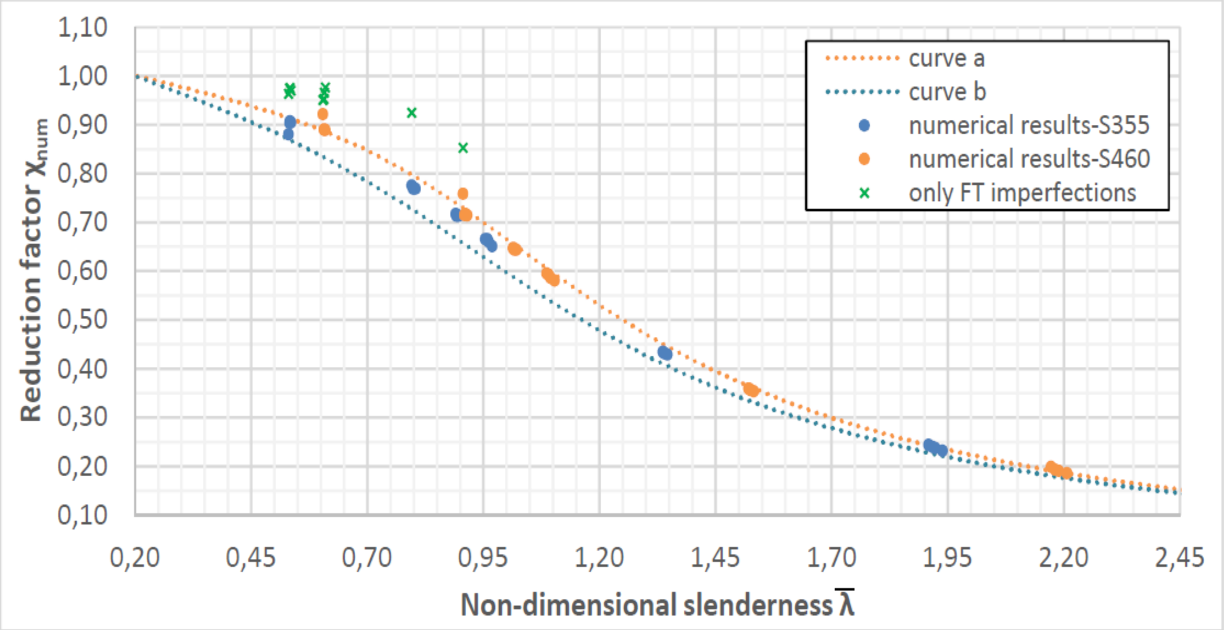
$$A_{eff} = A - 2ct(1-\rho)$$

$$\bar{\lambda}_p = \sqrt{\chi_{min}} \frac{c/t}{18{,}6\varepsilon}$$

where c=h-t-r

- $\rho = 1$, for $\bar{\lambda}_p \leq 0{,}748$
- $\rho = \frac{\bar{\lambda}_p - 0{,}188}{\bar{\lambda}_p^2}$, for $\bar{\lambda}_p > 0{,}748$

- There is a tendency of the angles to **buckle along weak axis!**
- Evidences through test and numerical studies
- **Simplify the calculations**
- EN1993-1-1 (2005) proposed curve b



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Single angle members
Member subjected to strong axis bending-LTB

Design resistance: $M_{u,Rd} = \chi_{LT} W_u \frac{f_y}{\gamma_{M1}}$

where: $\bar{\lambda}_{LT} = \sqrt{\frac{W_u \cdot f_y}{M_{cr}}}$

Critical LTB moment: $M_{cr} = C_b \frac{0{,}46 \cdot E \cdot h^2 \cdot t^2}{l}$

$$C_b = \frac{12.5M_{max}}{2.5M_{max} + 3M_A + 4M_B + 3M_C} \leq 1.5$$

$W_u = \alpha_{i,u} W_{el,u}$, i = 2, 3, 4

$\alpha_{2,u} = 1{,}5$ for class 1 or 2

$\alpha_{3,u} = \left[1 + \left(\frac{26{,}3\varepsilon - c/t}{26{,}3\varepsilon - 16\varepsilon}\right) \cdot (1{,}5 - 1)\right]$ for class 3

$\alpha_{4,u} = W_{eff,u} / W_{el,u} = \rho_u^2$ for class 4

$$\bar{\lambda}_p = \sqrt{\chi_{LT}} \frac{c/t}{35{,}58\varepsilon}$$

- $\rho_u = 1$, for $\bar{\lambda}_p \leq 0{,}748$
- $\rho_u = \frac{\bar{\lambda}_p - 0{,}188}{\bar{\lambda}_p^2}$, for $\bar{\lambda}_p > 0{,}748$

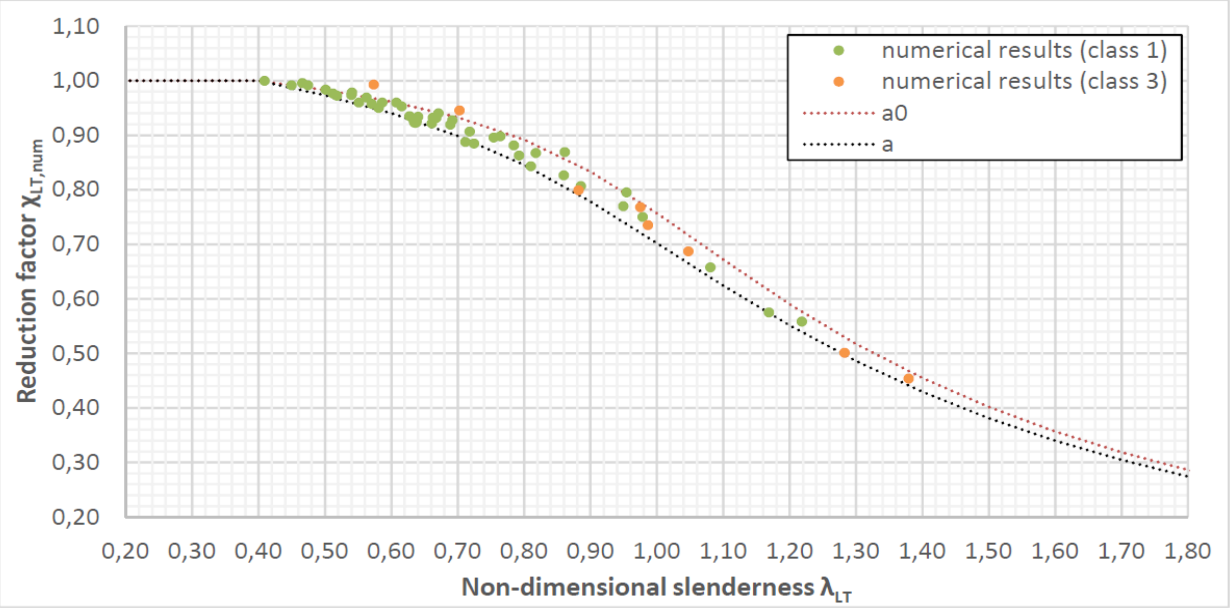
LTB may be ignored and χ_{LT} =1,0 when:

- $\bar{\lambda}_{LT} \leq \bar{\lambda}_{LT,0}$ with $\bar{\lambda}_{LT,0} = 0{,}4$
- $\frac{M_{Ed}}{M_{cr}} \leq \bar{\lambda}_{LT,0}{}^2$
- $\frac{N_{Ed}}{N_{bu,Rd}} > 0{,}5$
- $\frac{N_{Ed}}{N_{bv,Rd}} > 0{,}5$

Buckling **curve a** with a doubling plateau should be used for LTB instead of **curve d** that the current code proposes

$$\chi_{LT} = \frac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^2 - \bar{\lambda}_{LT}^2}} \quad \text{but} \begin{cases} \chi_{LT} \leq 1{,}0 \\ \chi_{LT} \leq 1/\bar{\lambda}_{LT}^2 \end{cases}$$

$$\Phi_{LT} = 0{,}5\left[1 + a_{LT}\left(\bar{\lambda}_{LT} - 0{,}4\right) + \bar{\lambda}_{LT}^2\right]$$



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Single angle members
Combine axial compression and bi-axial bending moment

- strong axis check

$$\left(\frac{N_{Ed}}{N_{bu,Rd}} + k_{uu}\frac{M_{u,Ed}}{M_{u,Rd}}\right)^{\xi} + k_{uv}\frac{M_{v,Ed}}{M_{v,Rd}} \leq 1$$

- weak axis check

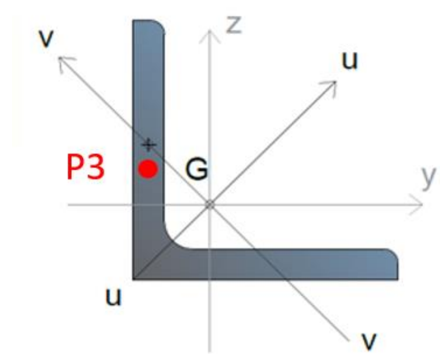
$$\left(\frac{N_{Ed}}{N_{bv,Rd}} + k_{vu}\frac{M_{u,Ed}}{M_{u,Rd}}\right)^{\xi} + k_{vv}\frac{M_{v,Ed}}{M_{v,Rd}} \leq 1$$

k_{ij} factors	
$k_{uu} = \frac{C_u}{1-\frac{N_{Ed}}{N_{cr,u}}}$ (4.32)	$k_{uv} = C_v$ (4.33)
$k_{vu} = C_u$ (4.34)	$k_{vv} = \frac{C_v}{1-\frac{N_{Ed}}{N_{cr,v}}}$ (4.35)
$C_u = 0{,}6+0{,}4\psi_u$ (4.36)	$C_v = 0{,}6+0{,}4\psi_v$ (4.37)
$-1 \leq \psi_u = \frac{M_{2u}}{M_{1u}} \leq 1$ (4.38)	$-1 \leq \psi_v = \frac{M_{2v}}{M_{1v}} \leq 1$ (4.39)

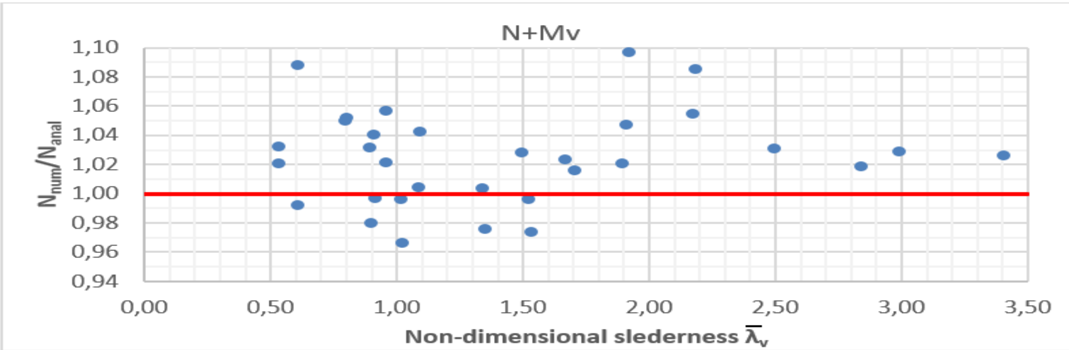
$c/t \leq 16\varepsilon$: $\xi = 2$

$16\varepsilon < c/t < 26{,}3\varepsilon$: $\xi = \left[1 + \left(\frac{26{,}3\varepsilon - c/t}{26{,}3\varepsilon - 16\varepsilon}\right) \cdot (2-1)\right]$

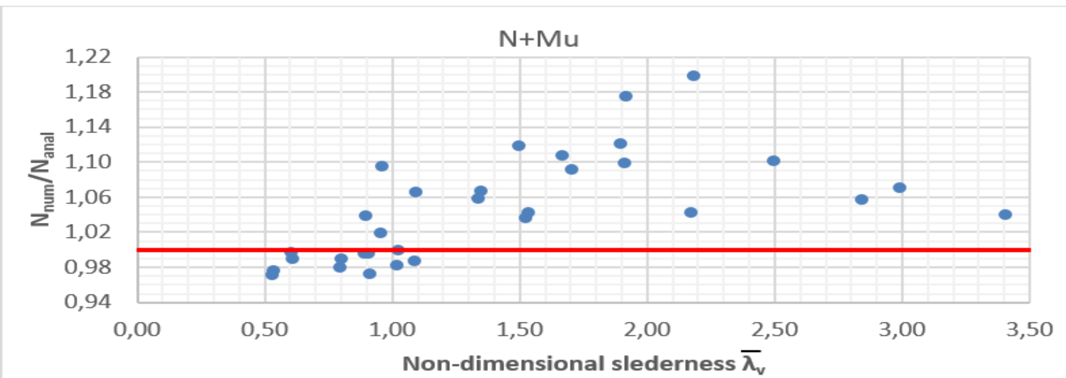
$c/t > 26{,}3\varepsilon$: $\xi = 1$



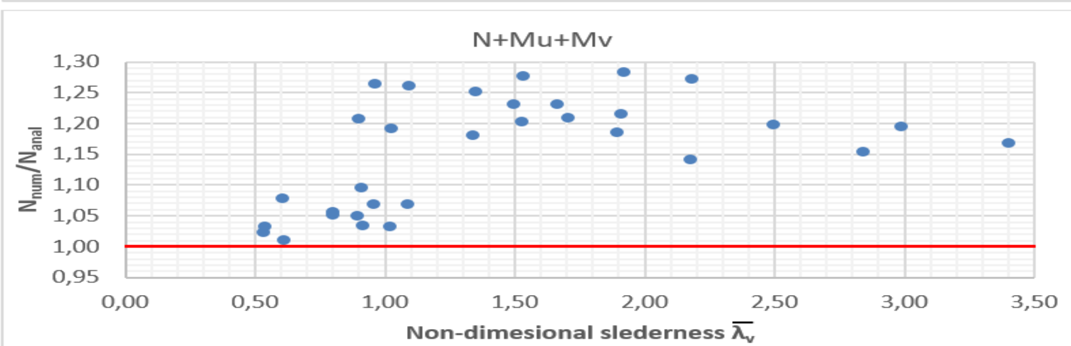
Single angle members
Combine axial compression and bi-axial bending moment



The mean value N_{num}/N_{anal} is equal to 1,03 with a standard deviation of 3,2%



The mean value N_{num}/N_{anal} is equal to 1,05 with a standard deviation of 5,09%



The mean value N_{num}/N_{anal} is equal to 1,15 with a standard deviation of 8,8%

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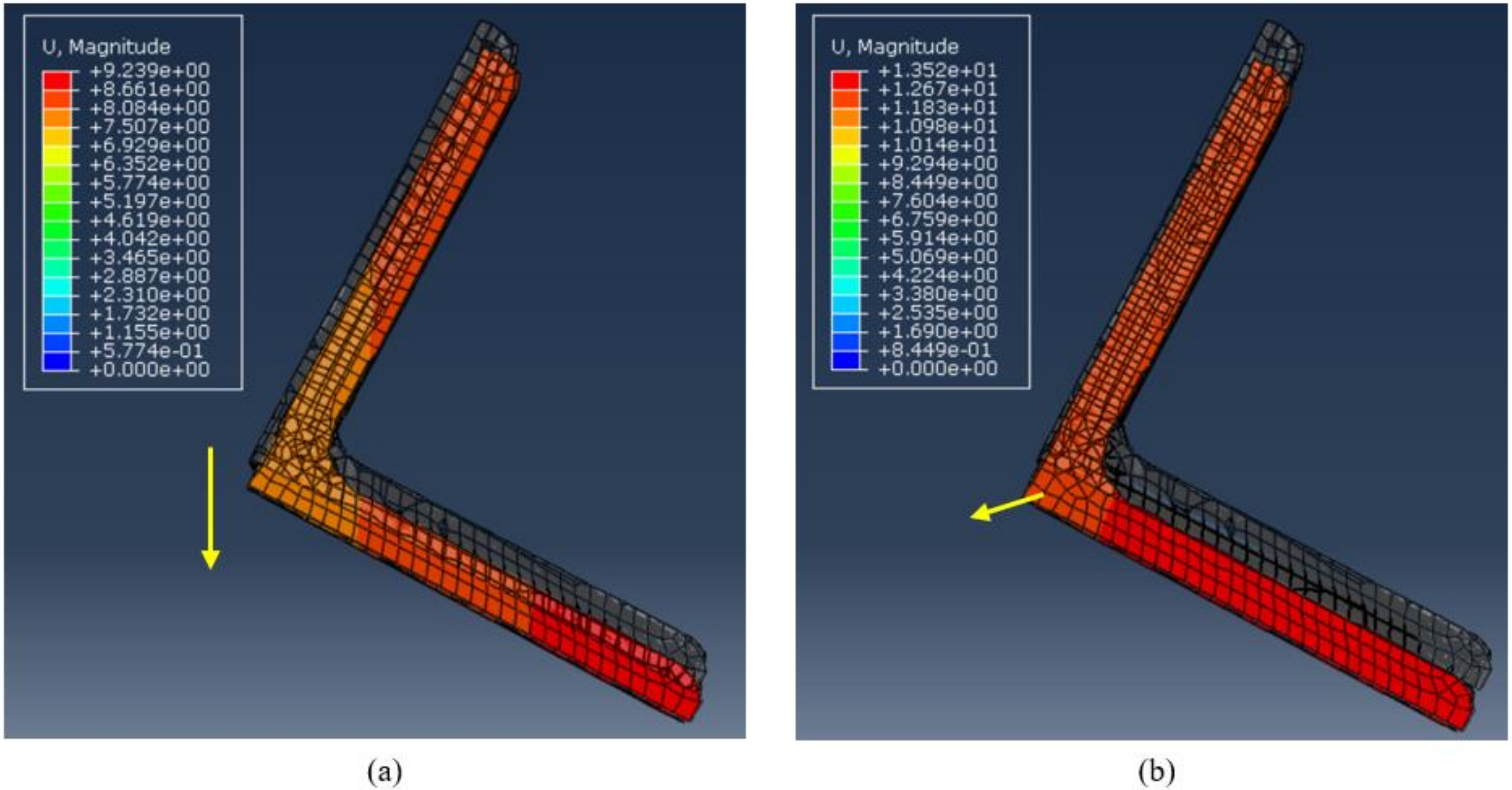
Single angle members
Combine axial compression and bi-axial bending moment



Movement of a profile subjected to an axial force and strong axis bending: (a) during loading-initial steps and (b) at the failure load

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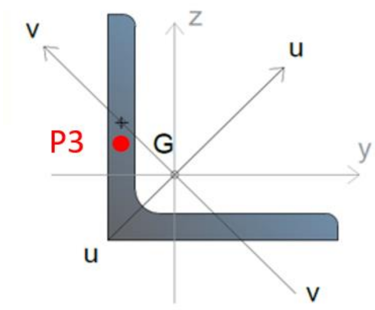
The general method has been adapted to fit better with angles through numerical and experimental validations.

$$\chi_{op} \cdot a_{ult,k} \geq 1{,}0$$

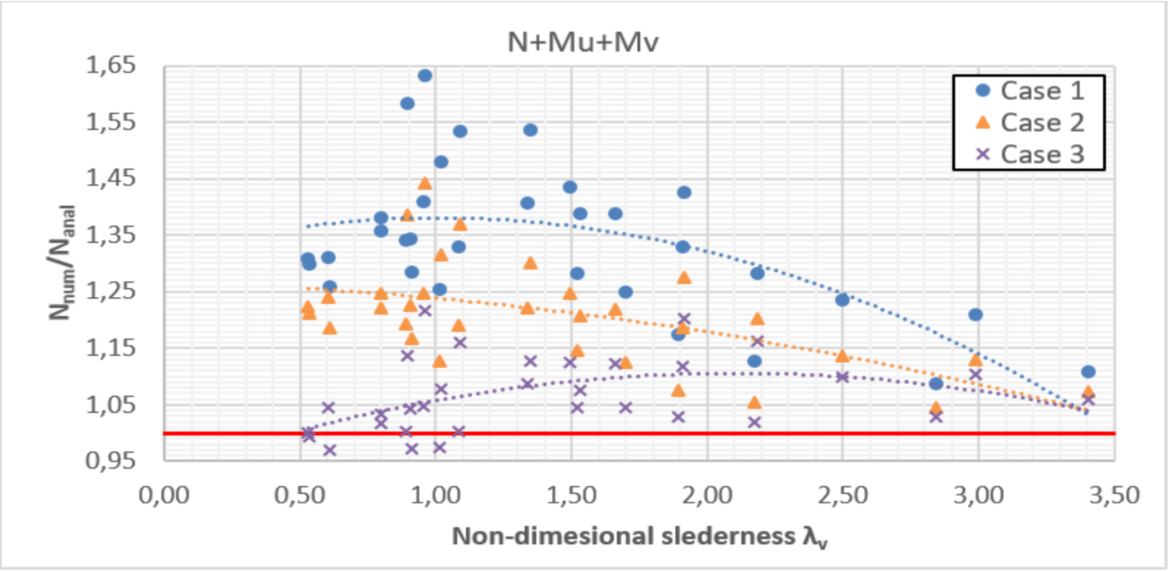
$$\chi_{op} = \min\{\chi_u; \chi_v\}$$

$$\alpha_{ult,k} = \frac{\sigma_{max}}{f_y} = \frac{\sigma_N}{f_y} + \frac{\sigma_{e_0}}{f_y} + \frac{\sigma_M}{f_y}$$

$$\overline{\lambda_{op}} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr,op}}}$$

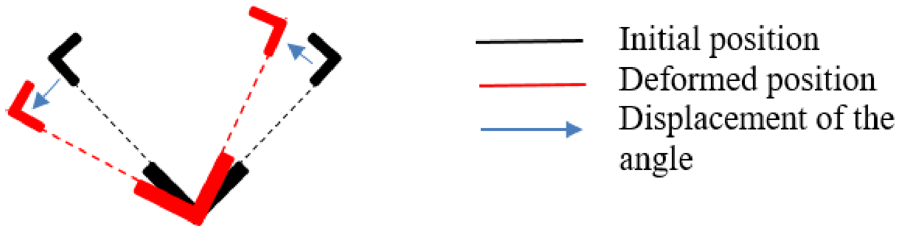


$\alpha_{cr,op}$ is the minimum load amplifier for the design loads to reach the elastic critical load of the structural component associated to **weak axis buckling**.

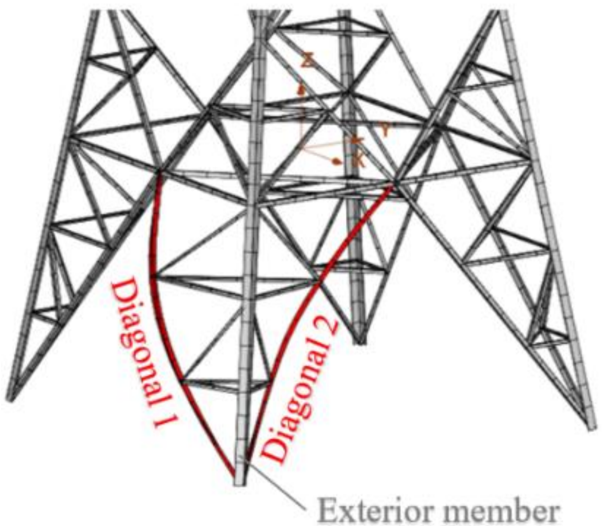


Single angle members
The segment instability

- A "segment instability" is defined as an instability mode associated to the buckling of more than one members forming a segment. In the present case the instability is associated to the buckling of the two diagonals of the leg.
- All the members (diagonals & exterior one) constituting the segment are stable individually and are able to resist to the applied maximum forces, as they have been initially designed to that. But the simultaneous buckling of the diagonals involving a longitudinal rotation of the main leg member, represents a "new mode" which has been seen to be relevant in various usual design situations.



- The diagonals moves laterally and bends about a geometrical axis.
- The main leg rotates about its longitudinal axis.
- The elements which "close the horizontal leg triangles" do not undergo any deformation; they are just translated.



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Single angle members
The segment instability

Simplified model

- The critical load multiplier a_{cr} may be given by the formula:

$$a_{cr} = \frac{2\pi^2 E I_y}{L^2 . (P_1 + P_2)}$$

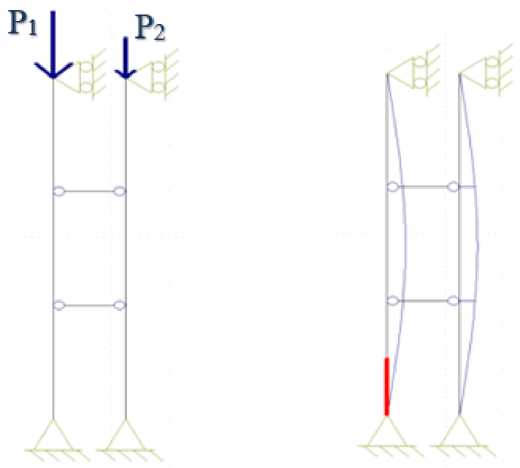
where,

I_y is the moment of inertia about y-y geometrical axis of the diagonal's cross-section;

L is the buckling length of the diagonal;

E is the modulus of elasticity;

P_1, P_2 are the axial forces in the two diagonals.



Equivalent model of the leg (left) and deformed shape (right)

- This model is independent of the number of horizontal "rigid triangles", and therefore may be generally used for segments with pyramidal configuration

> The simplified equivalent model disregards the rotational restraint of the main leg member as well as the continuity of the diagonals above the leg level

Single angle members
The segment instability

Final model

- The final model has been developed so as taking into account the rotational rigidity of the main leg.
- Simplified formulae based on the geometry, cross-section and material properties.

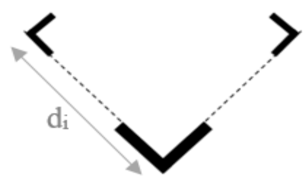
- The **critical load multiplier a_{cr}** is: $a_{cr} = \frac{N_{cr}}{P_1+P_2}$
- N_{cr} is the **critical load of the equivalent column** representing the segment:

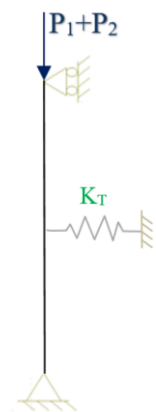
$$N_{cr} = \frac{\pi^2 E I_{y,tot}}{L^2} + \frac{3}{16} K_T L$$

K_T is the **stiffness of the unique spring restraint**, equals $\frac{4}{9}(2\mathrm{R}_{\mathrm{mean}})$

- The mean value of the **lateral restraint R** of the diagonals is:

$$R_{mean} = \frac{3C}{2L_{ext}} \cdot \frac{1}{n} \sum_{i=1}^{n} \frac{1}{d_i^2}$$





Equivalent final proposed model of the leg

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Single angle members
The segment instability

Ultimate resistance of the leg

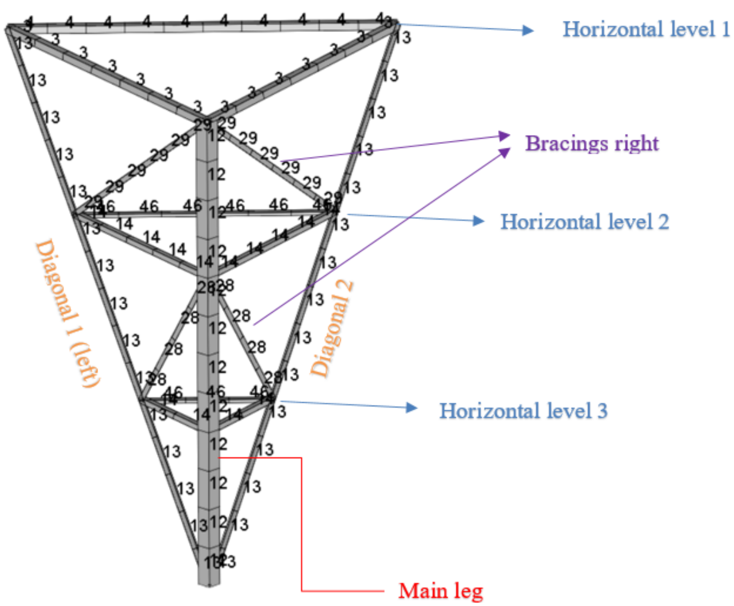
- For both proposed models, an estimation of the carrying capacity of the column in compression can be roughly done through the Merchant-Rankine approach:

$$\frac{1}{a_u} = \frac{1}{a_{cr}} + \frac{0{,}96}{a_{pl}}$$

- where α_{pl} can be evaluated by the following equation: $\alpha_{pl} = \frac{2 \cdot N_{pl}}{P_1+P_2} = \frac{2 \cdot A_{diag} f_y}{P_1+P_2}$

Application in practice

Member	CS code	Cross-section	Length [m]
Diagonal 1 (left)	13	75x75x4	6,00
Diagonal 2 (right)	13	75x75x4	6,00
Main leg	12	150x150x13	5,00
Horizontal level 2	14	60x60x4	1,827
Horizontal level 3	14	60x60x4	0,913



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Single angle members
The segment instability

Results obtained through FINELG and the simplified analytical formula

Load combination	P_1 [kN]	P_2 [kN]	$\alpha_{cr,FIN}$ [-]	No of eigenmode	$\alpha_{cr,anal,1}$ [-]	α_{pl} [-]	$\alpha_{cr,anal,1}/\alpha_{cr,FIN}$ [-]	$\alpha_{cr,anal,1}/\alpha_{pl}$ [-]
$G+W_y$	30,00	0,00	1,37	1	1,21	13,639	0,881	0,0884
$G+W_x$	7,26	2,51	4,28	4	3,70	41,889	0,866	0,0884
G_{tower}	0,91	0,92	23,99	12	19,75	223,346	0,823	0,0884
Wx	5,78	1,37	6,42	1	5,06	57,227	0,788	0,0884
Wy	3,13	29,92	1,48	1	1,10	12,380	0,740	0,0884
Mean value	---	---	---	---	---	---	0,820	0,0884

$\lambda_1=3,363 \rightarrow \alpha_{u,1}=0,922\alpha_{cr,anal,1}$

Results obtained through FINELG and the final analytical formulae

Load combination	P_1 [kN]	P_2 [kN]	$\alpha_{cr,FIN}$ [-]	No of eigenmode	$\alpha_{cr,anal,2}$ [-]	α_{pl} [-]	$\alpha_{cr,anal,2}/\alpha_{cr,FIN}$ [-]	$\alpha_{cr,anal,2}/\alpha_{pl}$ [-]
$G+W_y$	30,00	0,00	1,37	1	1,33	13,639	0,973	0,0978
$G+W_x$	7,26	2,51	4,28	4	4,10	41,889	0,957	0,0978
G_{tower}	0,91	0,92	23,99	12	21,84	223,346	0,910	0,0978
Wx	5,78	1,37	6,42	1	5,60	57,227	0,872	0,0978
Wy	3,13	29,92	1,48	1	1,21	12,380	0,818	0,0978
Mean value	---	---	---	---	---	---	0,906	0,0978

$\lambda_2=3,198 \rightarrow \alpha_{u,2}=0,914\alpha_{cr,anal,2}$

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Built-up members

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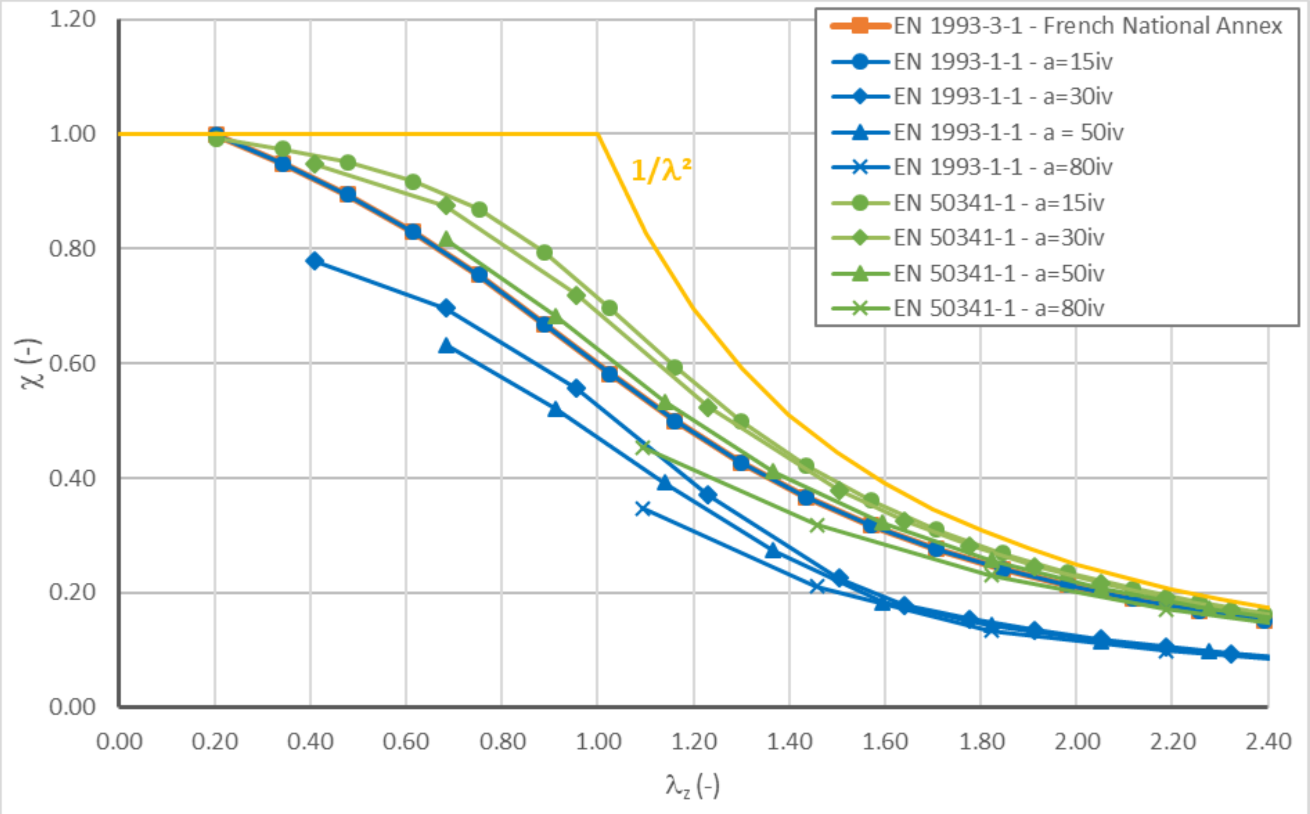
Built-up members – Context

<u>Context of the study</u>

- In Eurocode 3 part 1-1, built-up members connected back-to-back are considered as homogenous if the distance between packing plates is less than **$15i_{min}$**
- Several design methods exist for higher packing plate distances
- But: **high discrepancy** between different design approaches for closely spaced built-up members



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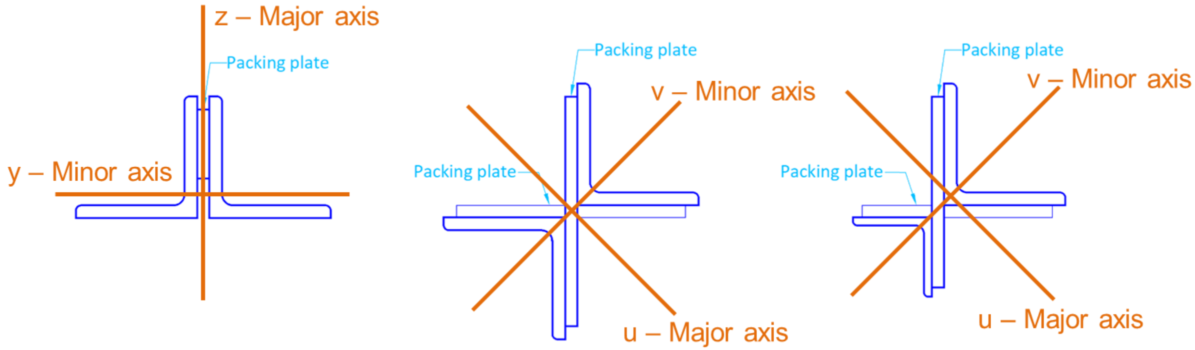
Built-up members – Objective and Methodology

Objective of the study

- Develop design method for major axis buckling of back-to-back connected specimens (BBE) **under compression**
- Develop design method for star battened specimens (SBE and SBU) **under combined compression and bending**

Scope of the study

BBE specimens SBE specimens SBU specimens



Methodology

- A total of **16 laboratory tests** on BBE, SBE and SBU specimens
- Extensive numerical simulation campaign to extend the experimental study

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Built-up members – Laboratory tests

Laboratory tests

Notation	Section	Steel grade	Total member length [mm]	Total number of packing plates	Level of pretension
BBE1	2 L 70x70x7	S355	1200	7	100%
BBE2/BBE5	2 L 70x70x7	S355	3600	19	100%/10%
BBE3	2 L 70x70x7	S355	2000	4	100%
BBE4/BBE6	2 L 70x70x7	S355	3600	6	100%/10%
SBE1	2 L 60x60x6	S355	2200	8	100%
SBE2/SBE5	2 L 60x60x6	S355	3000	10	100%/10%
SBE3	2 L 60x60x6	S355	3000	8	100%
SBE4/SBE6	2 L 60x60x6	S355	4000	10	100%/10%
SBU1	L 80x80x8 + L 70x70x7	S355	2200	8	100%
SBU2	L 80x80x8 + L 70x70x7	S355	3000	10	100%
SBU3	L 80x80x8 + L 70x70x7	S355	3000	8	100%
SBU4	L 80x80x8 + L 70x70x7	S355	4000	10	100%

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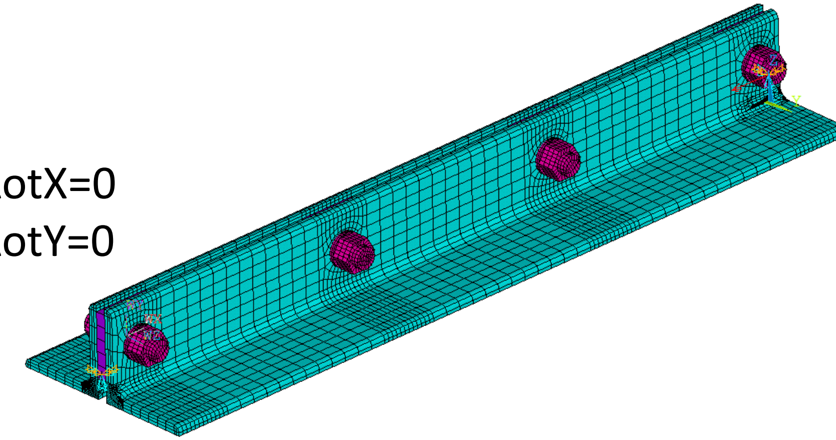
Built-up members – Numerical simulations

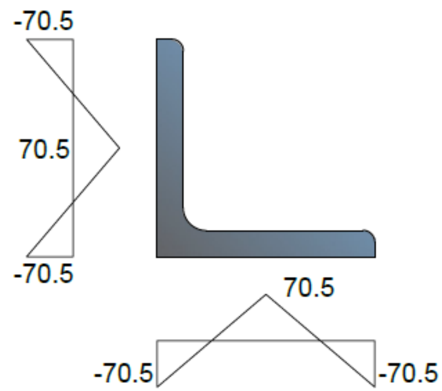
Numerical model

- Boundary conditions:



- Material law : Elastic-perfectly plastic
- Geometric imperfections: Eigen mode affine with amplitude L/1000

- Residual stresses:



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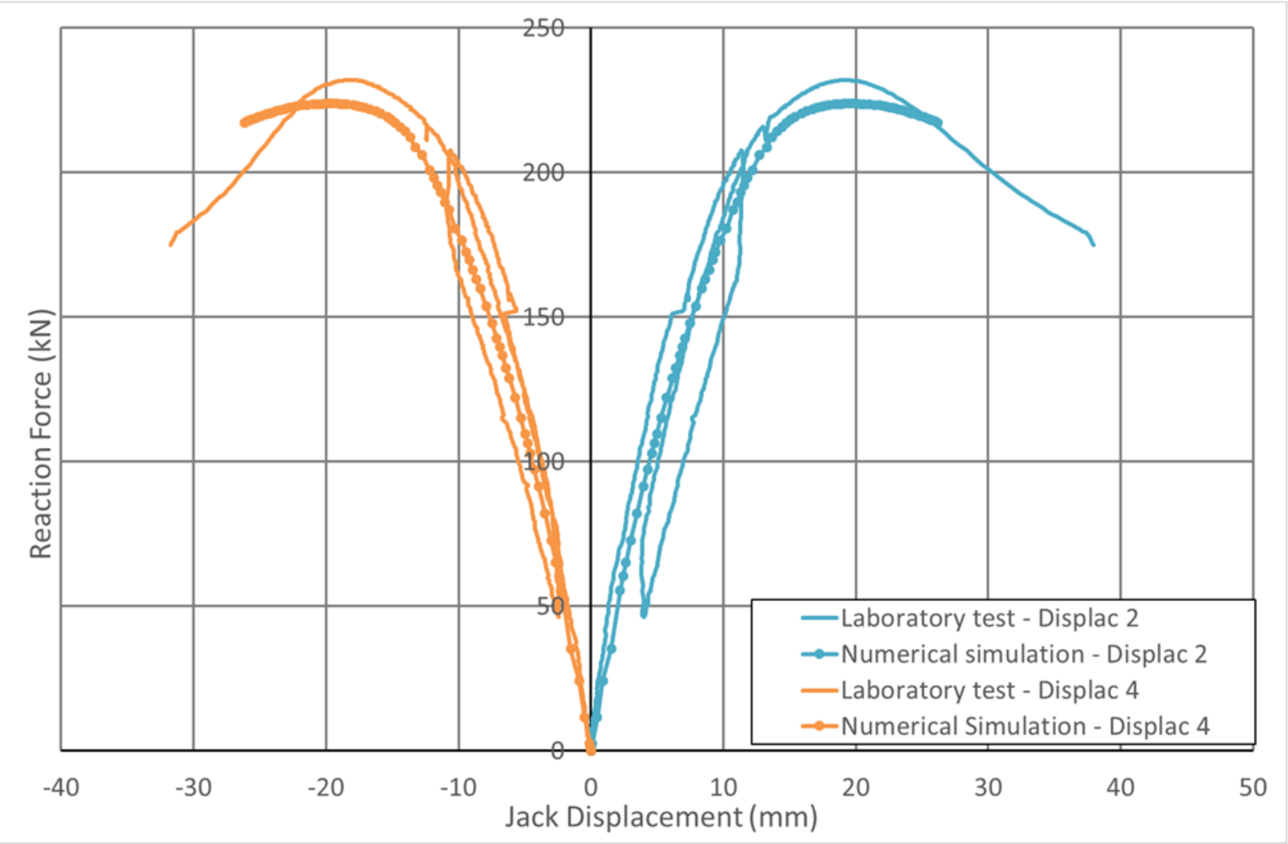
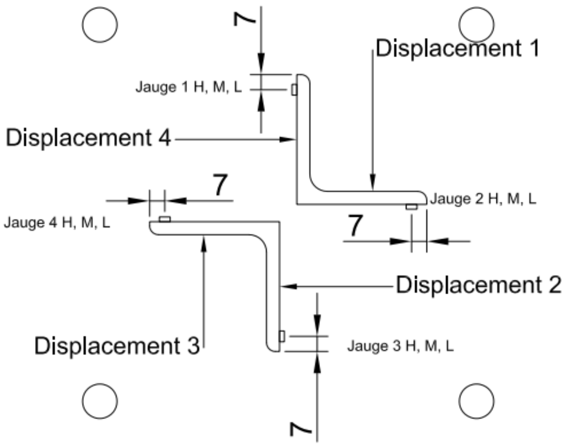
Built-up members – Numerical simulations

Numerical model - Validation

- SBU1 : L = 2200 mm – 2x2 intermediate packing plates





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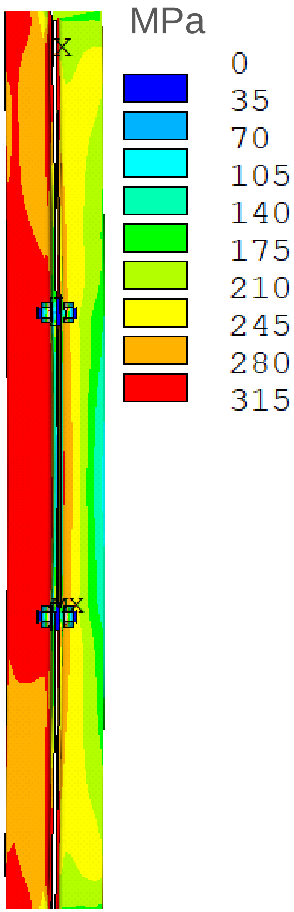
Built-up members – Numerical simulations

Numerical parametric study:



Parameter	Value
Cross section	BBE: L70.70.7 L150.150.15
	SBE: 2L70.70.7 2L150.150.15
	SBU: L90.90.9+L60.60.6 L150.150.15+L80.80.8
Packing plate thickness	= $t_{Section}$ (in case of SBU minimum thickness)
Packing plate distance	15i_{min} (only BBE), 30i_{min}, 50i_{min}, 70i_{min}, 90i_{min}
Member slenderness	0,4 – 2,0 (5 values)
Bolt pretension	0, 10% of nominal preloading, 100% of nominal preloading
Bolt diameter	According to recommendations for each section
Type of connection	Fitted bolts, Snug tight bolts, preloaded bolts
Steel grades	S235, S355, S460
Loading	Axial force, Axial force + bi-axial bending (10 combinations)

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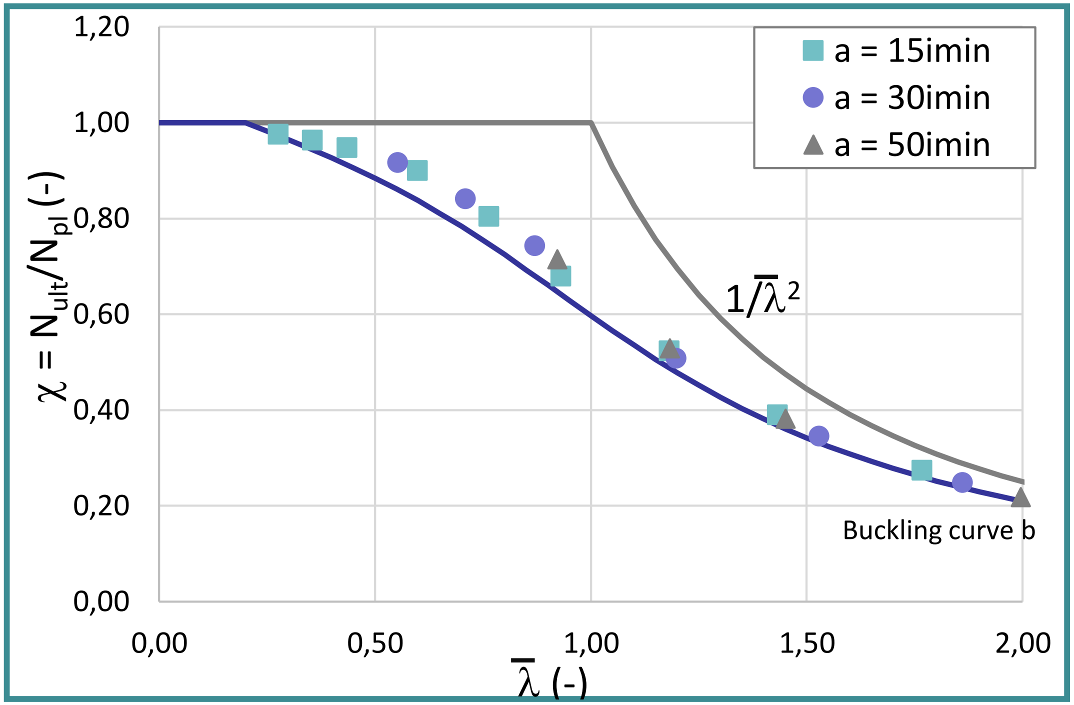
Built-up members – Design model BBE

Outcome of the numerical study – **BBE fitted bolts**:



$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr,z,Sv}}} \rightarrow N_{cr,z,Sv} = \frac{1}{\frac{1}{N_{cr,z,BBE}} + \frac{1}{S_v}}$$

$$\begin{cases} N_{cr,z,BBE} = EI_{z,BBE}\left(\frac{\pi}{L}\right)^2 \\ S_v = \frac{1}{\frac{a^2}{24EI_{v,ch}}} \end{cases}$$

→ Specific to the connection type

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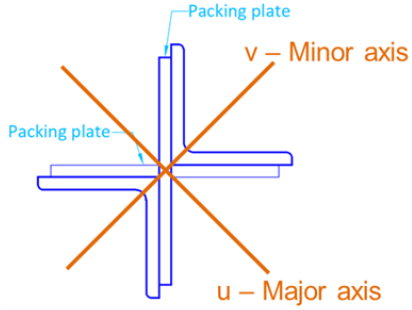
Built-up members – Design model SBE and SBU

Outcome of the numerical study – **SBE and SBU**:

- Flexural buckling under axial compression force (no torsional buckling mode)

$$\left(\frac{N_{Ed}}{N_{bv,Rd}} + k_{vu}\frac{M_{u,Ed}}{\chi_{LT} M_{u,Rd}}\right)^{\xi} + k_{vv}\frac{M_{v,Ed}}{M_{v,Rd}} \leq 1$$

$$\left(\frac{N_{Ed}}{N_{bu,Rd}} + k_{uu}\frac{M_{u,Ed}}{\chi_{LT} M_{u,Rd}}\right)^{\xi} + k_{uv}\frac{M_{v,Ed}}{M_{v,Rd}} \leq 1$$



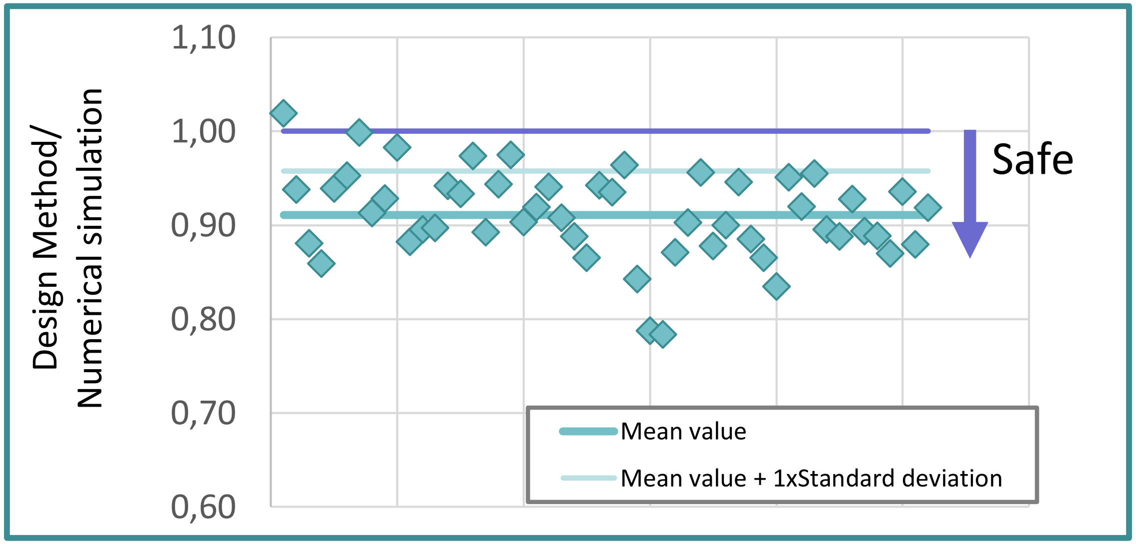
1) Interaction factors as for single angle section members (calculated with $N_{cr,Sv}$)
2) Exponent $\xi = 1{,}7$
3) $N_{bu,Rd}$ and $N_{bv,Rd}$ based on buckling curve *b* and $N_{cr,Sv}$
4) $M_{u,Rd} = 0{,}9M_{pl,u,Rd}$; $M_{v,Rd} = 0{,}9M_{pl,v,Rd}$
5) χ_{LT} determined with reduction curve *a* and $M_{cr}(I_{v,Sv})$

Built-up members – Design model SBE and SBU

Comparisons **SBE fitted bolts**:

$$\left(\frac{N_{Ed}}{N_{bv,Rd}} + k_{vu}\frac{M_{u,Ed}}{\chi_{LT} M_{u,Rd}}\right)^{\xi} + k_{vv}\frac{M_{v,Ed}}{M_{v,Rd}} \leq 1$$

$$\left(\frac{N_{Ed}}{N_{bu,Rd}} + k_{uu}\frac{M_{u,Ed}}{\chi_{LT} M_{u,Rd}}\right)^{\xi} + k_{uv}\frac{M_{v,Ed}}{M_{v,Rd}} \leq 1$$



- Design proposal is safe and sufficiently precise
- Design proposal is more conservative for interaction N+M_u due to the safe sided linear interaction

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Built-up members – Summary

Summary of the design proposal:

Common steps for all closely spaced built-up members

Step 1) Determine the shear stiffness S_v depending on the type of connection

Step 2) Determine the effective critical axial force $N_{cr,Sv}$ for relevant buckling axis

Step 3) Determine flexural buckling reduction factor χ based on curve *b*

Final step for BBE

Step 4BB) Verify the buckling resistance $\frac{N_{Ed}}{N_{b,Rd}} \leq 1{,}0$

Additional steps for SBE/SBU

Step 4SB) Determine the lateral torsional buckling reduction factor χ_{LT} based on curve *a*

Step 5SB) Determine interaction factors k_{ij} with $N_{cr,Sv}$

Step 6SB) Apply the interaction equations

$$\left(\frac{N_{Ed}}{N_{bv,Rd}} + k_{vu}\frac{M_{u,Ed}}{\chi_{LT}M_{u,Rd}}\right)^{\xi} + k_{vv}\frac{M_{v,Ed}}{M_{v,Rd}} \leq 1$$

$$\left(\frac{N_{Ed}}{N_{bu,Rd}} + k_{uu}\frac{M_{u,Ed}}{\chi_{LT}M_{u,Rd}}\right)^{\xi} + k_{uv}\frac{M_{v,Ed}}{M_{v,Rd}} \leq 1$$

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Thank you for your attention

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